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On the evolutionary dynamics of complexity and consciousness

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The perennial debate about the possible directionality of evolution, as indicated by the apparent increase in the complexity of living systems over time, has recently witnessed renewed arguments in favor of the growth of complexity being “entropic,” that is, consistent with the growth of entropy as it is construed in thermodynamics. Here, I offer a brief review of formal treatments of complexity and of evolutionary mechanisms that are capable of causing it to increase. I then propose that both the evolutionary emergence and the individual learning of basic phenomenal awareness, a type of consciousness, are characterized by the same time-asymmetrical dynamics. Like life itself, biological consciousness arguably evolves towards greater complexity, and for the same reasons.

KEYWORDS

complexity, consciousness, evolutionary dynamics, entropy, learning, phenomenal awareness, biological consciousness, dynamical emergence theory

1 Introduction

> The enormous *number* of animals in the world depends of [*sic*] their varied structure and complexity. — hence as the forms became complicated, they opened *fresh* means of adding to their complexity. — but yet there is no *necessary* tendency in the simple animals to become complicated although all perhaps will have done so from the new relations caused by the advancing complexity of others.

> *Notebooks on transmutation of species*, Part IV, Fourth notebook [E] (October 1838 – 10 July 1839).

> — Charles Darwin (1960, note 95, emphasis in the original).

Does evolution tend to lead to an increase in the complexity of living systems? The terse note quoted in the epigraph shows that Darwin believed that it does—but not necessarily across the board.[1] Here, I revisit the question of the evolutionary dynamics of complexity, including the relationship between complexity and entropy, about which much has been written in recent years. I then take up a hitherto seldom discussed possibility that the evolutionary tendency towards increasing complexity might extend to basic *consciousness*, the latter exemplified by simple perceptions, such as that of the taste of a wine or the smell of a flower. As an advocate of Dynamical Emergence Theory or DET (Moyal et al., 2020; Edelman, 2023), I construe basic consciousness as the

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[1] Regarding the importance of the choice of word “tend”: see (Brandon and McShea, 2020, p.7). Mumford and Anjum (2018) introduce a formal notion of tendency as a modality, supplementing the Aristotelian four.

process of autodiagnosis, or intrinsic discernment, by a dynamical cognitive-computational system of its own representational states.

With Darwin's informal observation as the starting point, I argue that evolution does encompass processes that tend to increase complexity. Several distinct mechanisms have by now been identified that can explain this tendency—which, again as noted by Darwin, need not result in a unidirectional or universal complexification. My survey of the literature yields at least three such mechanisms: two neutral drift-like and one adaptational. I will introduce these mechanisms here and present them in more depth later (Sections 3, 4).

The first of these mechanisms consists in an obligatory tendency, in any evolutionary system characterized by variation and heredity alone, of complexity to increase (which, however, can be masked, or amplified, by selection; McShea and Brandon, 2010; McShea et al., 2019). The second mechanism too is, as a matter of principle, independent of selection (but may still be modulated by it as well). Specifically, an increase in the complexity of an evolving system can go hand in hand with an increase in the volume of the "phase space" available to it for evolutionary exploration—and therefore with the entropy of its configurations (e.g., Wicken, 1979; Brooks and Agosta, 2012; Jeffery et al., 2019). If that is the case, the direction of increasing complexity becomes "entropic" — that is, subject to the same probabilistic asymmetry that underpins the Second Law of thermodynamics. As we shall see, this is related to the idea in Darwin's note, which may be captured by the slogan *complexity breeds complexity*.

The third family of mechanisms are selectional "ratchet effects" (e.g., McElreath et al., 2018; De Castro and McShea, 2022) that can amplify random complexity increases driven by the first two types of mechanisms. If complexity is defined by the number of the system's components (more about which in the next section), then the following argument, due to [Saunders and Ho (1976), p.381], applies:

> [C]onsider a system which is at or near a local peak of fitness, i.e. which has achieved a locally optimal organization. Then the random removal of a component must tend to make the system less fit than before, since otherwise the optimal organization would have been that in which the component in question was disconnected from the system. But the random addition of a component, while it too may (and probably usually does) lead to a decrease in fitness, also allows the possibility of an increase.

An accumulation of the increases in complexity stemming from this dynamic would result in their effective acceleration — "ratcheting up the ratchet" (Tennie et al., 2009).

The remainder of this paper is structured as follows. Section 2 is an overview of some applicable definitions of complexity and of the different senses in which it can be said to increase. In Sections 3–5, I discuss previous work on the evolutionary tendency toward increasing complexity. Section 6 then seeks to extend those ideas to the complexity of cognition and consciousness, construed as self-diagnosing brain dynamics, on both evolutionary and developmental time scales. Finally, Section 7 offers concluding remarks and mentions some open questions.

2 Preliminaries

The notion that evolution tends to turn out progressively more complex life forms has always held great intuitive appeal. After all, are not we, a latecomer species, so much more complex than the bacteria in our gut? Making this notion formal and precise enough to be empirically assessed and incorporated into evolutionary theory is, however, a difficult undertaking. A basic requirement is that the definition of complexity not be circular (as in "that, which increases over evolutionary time"; McShea, 1997). Further, care must be taken, lest the claim of increasing complexity reduces to the pre-scientific concept of the Great Chain of Being (McDonald Pavelka, 2002; Brandon and McShea, 2020).[2] Much progress has been achieved in the last several decades in formalizing and quantifying complexity so as to meet both these requirements. In this section, I synthesize what I perceive to be the key proposals from the literature.

2.1 How should complexity be defined?

In computing and information sciences and, by extension, in the science of complex systems, there are several accepted definitions of complexity (see Aaronson et al., 2014 for an overview). Choosing among these depends on the nature of the system or the task at hand. A key measure, Kolmogorov complexity, which applies to formal expressions such as a string drawn from a fixed alphabet, is defined as the length of the shortest computer program that generates it.

It is unclear, to say the least, how to apply such measures to a living system; as [McShea (1997), p.84] puts it, "How would we calculate the length of the shortest algorithm that will generate a sponge?"[3] Consequently, discussions of complexity in biology have traditionally tended to be informal [exemplified by Maynard Smith's (1972), p.205] equating complexity with "high degree of improbability" in a passage quoted in Section 3 below), or else to postulate simple formal measures that are arguably applicable to living systems.

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[2] The concept of the Great Chain of Being has long been a mainstay of "race science" and eugenics (Landau, 1997; Quintyn, 2023). Indeed, the increasing complexity thesis has been invoked by eugenicist J. S. Huxley, who claimed that "evolution is a . . . process, directional in time and therefore irreversible, which in its course generates ever fresh novelty, greater variety, more complex organization, higher levels of awareness, and increasingly conscious mental activity" (Huxley, 1955, p.4). Using the complexity thesis to justify racism or eugenics is a misapplication of science (McDonald Pavelka, 2002). Whether or not consciousness does in fact have an evolutionary tendency to become more complex is a question that I consider in section 6.

[3] Kolmogorov complexity is difficult to estimate. Because it is conceptually related to compressibility, [Aaronson et al. (2014), p.12] has suggested the following workaround: "The estimated complexity of the state, $K(S)$, is the file size of the thresholded, coarse-grained array after compression [by gzip]. Analogously, the estimated entropy of the automaton state is the compressed file size of the fine-grained array."

One such measure of complexity is the number of distinct part types (in the case of metazoans, these can be cell types) that comprise the system. [Saunders and Ho (1976), p.377] saw it as uncontroversial, citing von Neumann (1966), who "defined the complexity of an automaton to be the number of components it contains and there does not appear to have been any serious disagreement with this choice, although for biological systems a better measure is the number of different types." [Von Neumann (1966), p.36] had in fact sounded less decisive: "It is not completely obvious how to measure the complexity of an automaton."[4] A few pages later, he comes close to conceiving of a measure that sounds a lot like Kolmogorov's: "You see that you can produce circuits which look complicated, but which are actually quite simple from the point of view of how they are synthesized and which have about the same complexity that they should have, namely, the complexity that grammar has" (von Neumann, 1966, p.46).

More recently, using the number of a system's part types as an estimate of its complexity has been endorsed as a reasonable compromise (McShea, 1997) and proved to be useful in practice (Fleming and McShea, 2013). Bailly and Longo (2009) include it as one of three components in their definition of complexity (the other two being morphological and functional complexity).[5] It serves as the basis for the quantitative formulation of a proposed law that captures the evolutionary trajectory of complexity, called by its developers "biology's first law" (McShea and Brandon, 2010; see also McShea et al., 2019; Brandon and McShea, 2020), to be discussed in Section 3. Meanwhule, I accept the definition of complexity as the number of distinctive parts in a system.

2.2 In what sense might complexity increase, and by what means?

The existence of mechanisms that cause system complexity to increase over evolutionary time does not imply that the complexity of all evolving systems will always grow. On the one hand, metazoans clearly are more complex than their single-cell ancestors under any reasonable definition of genetic, morphological, and behavioral complexity. On the other hand, ever since their appearance on the evolutionary scene hundreds of millions of years ago, metazoans have always coexisted with "simple" microbial life-forms such as bacteria and archaea, many of them free-living in the environment and others host-associated, living in and on multicellular organisms.

Still, asserting a universal rise in complexity is not out of the question, as long as we are precise about what it is that we assert. Specifically, the claim that complexity rises over evolutionary (or developmental) time may pertain to the minimal, mean, or maximal complexity of the systems in question (McShea, 1997). Thus, Darwin's (1960) remark that "there is no *necessary* tendency in the simple animals to become complicated" may be interpreted as making the claim to be about the *maximum complexity*, estimated over the various species in question. This would exempt the proponents of the thesis of rising complexity from having to account for the metazoans having joined, rather than replaced, unicellular life forms in the arena of life, as well as for the down- and not only up-swings of complexity in specific evolutionary lineages.

Evolutionary changes in complexity can in principle be caused by a variety of mechanisms. A key distinction can be made between two kinds: *driven*, characterized by a bias in the direction of either increasing or decreasing complexity; and *passive*, characterized by an absence of any bias or driving force (McShea, 1997). In the next section, I begin with an overview of the passive causes of evolutionary complexity increase.

3 The growth of complexity in the absence of bias

By what means might the complexity of life forms increase over evolutionary time, if there is no bias in favor of higher complexity? In this section, I briefly mention two passive (non-biased) mechanisms, one rooted in the basic mathematical consequence of heritable variation and the other having to do with entropy and a probabilistic dynamics of the same kind that underlies the Second Law of thermodynamics.

3.1 Complexity and heritable variation

Let us consider first a mechanism that Maynard Smith did not think much of. In the same paragraph where he casually equates complexity with improbability, [Maynard Smith (1972), p.205] offers the following answer to the question of increasing complexity:

> The obvious and uninteresting explanation of the evolution of increasing complexity is that the first organisms were necessarily simple, because the "origin of life" is the origin, without natural selection, of entities capable subsequently of evolving by natural selection, and without selection there is no mechanism for generating a high degree of improbability — i.e. complexity. And if the first organisms were simple, evolutionary change could only be in the direction of complexity.

Immediately after invoking selection, Maynard Smith states that any "evolutionary change" will increase complexity, given that the first organisms were simple. Indeed, such an increase need not depend on selection and can be entirely passive: as long as

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[4] The continuation of this quote is instructive: "For computing machines, probably the reasonable way is to count how many vacuum tubes are involved. This is somewhat ambiguous, because certain current types of vacuum tubes are in reality two vacuum tubes inside one envelope, in which case one is never quite sure which one of the two he is talking about. Another reason is that a great deal enters into computing machine circuitry aside from vacuum tubes: electrical equipment like resistors, capacitances, and possibly inductances. Nevertheless, the ratio of these to the vacuum tubes is tolerably constant, and therefore the number of tubes is probably a reasonable measure of complexity."

[5] In cultural anthropology too, a combination of number of parts and functional context is used to define complexity (Read and Andersson, 2020).

complexity is bounded from below, the average complexity of *randomly* evolving systems can be expected to grow, simply because a random walk in such a complexity space can in the long run only result in a net drift in the direction of increasing complexity [see (McShea, 1997; Figure 3B) for an illustration and (Bailly and Longo, 2009; Longo and Montévil, 2012) for an independently developed, mathematically explicit version of this argument, motivated by the work of S. J. Gould (1994)].

While McShea's 1997 paper had been skeptical about the hypothesis of increasing complexity, his subsequent work fully validated it. The passive drift explanation of the evolutionary increase in complexity (as measured by the number of part types) turned out to be far from "uninteresting." Indeed, it led to a quantitative formulation of "biology's first law" (McShea and Brandon, 2010; McShea et al., 2019; Brandon and McShea, 2020).[6] [McShea and Brandon (2010), p.2] explain what they call the Zero-Force Evolutionary Law, or ZFEL, as follows:

> [R]ising diversity and complexity are the null expectation, the predicted outcome for evolution in the total absence of selection and other forces. They are the zero-force expectation. The reason is simply that variation arises in biological systems, and when heritable it accumulates, with the result that variances tend to increase.

In a later publication, [Brandon and McShea (2020), p.7] state the ZFEL as follows:

> ZFEL (general formulation): In any evolutionary system in which there is variation and heredity, there is a tendency for diversity and complexity to increase, one that is always present but may be opposed or augmented by natural selection, other forces, or constraints acting on diversity or complexity.

Very importantly, [Brandon and McShea (2020), p.7] note that the ZFEL, which is a *passive* mechanism for complexity growth, can be counteracted by *active* ones: "The critical word . . . is 'tendency.' When forces or constraints are present, diversity and complexity have a tendency to increase" (rather than increasing necessarily, as per the ZFEL).[7] I discuss this issue further in Section 4.

3.2 Complexity and entropy

I now consider a second passive cause of complexity growth. Like the ZFEL, it takes the form of a probabilistic tendency, which in this case is analogous to that, which underwrites the Second Law of thermodynamics. Specifically, complexity growth can be *entropic* in the sense that complexity increases concomitantly with increasing entropy, the latter being the probable direction of the system's progression through its configuration space,[8] as described by the Second Law (Saunders and Ho, 1976; Wicken, 1979; Saunders and Ho, 1981; Wiley and Brooks, 1982; Collier, 1986; Aberle, 1987; Brooks and Agosta, 2012; Jeffery et al., 2019). Note that we need not invoke the Second Law as such: as explained by Jeffery et al. (2019), the probabilistic dynamics in question is more broadly applicable and does not require that the system be closed or approach equilibrium.

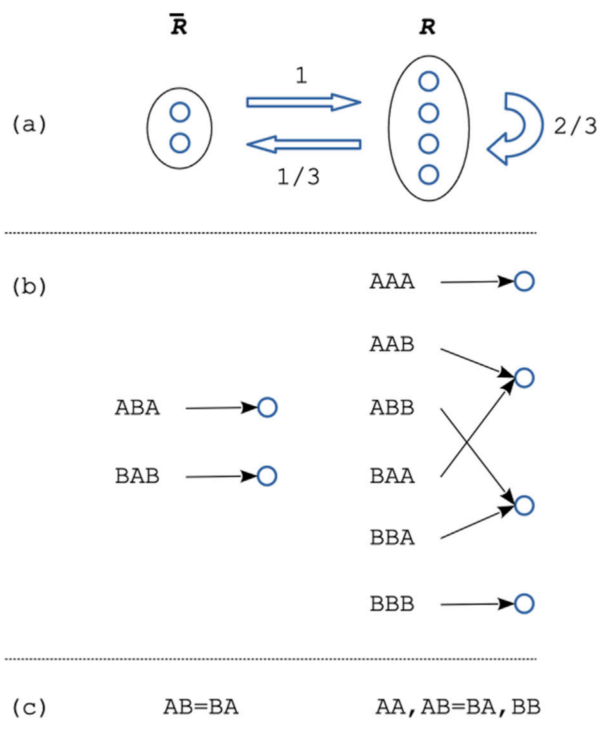

FIGURE 1
A toy example illustrating the concepts of micro- and macrostates and the dynamics of entropy and complexity in the space of three-symbol strings over a two-symbol alphabet, {A, B}. Microstates correspond to specific strings. Random transitions between these are precipitated by single-symbol changes (A to B or B to A) and are assumed to be equiprobable. Assuming left-right mirror symmetry, there are six distinct microstates, indicated by small circles in **(a,b)**. These belong to two macrostates: R, which comprises microstates that may contain symbol repeats, as shown on the right in **(a,b)**; and $\bar{R}$, which comprises microstates without symbol repeats, as shown on the left. The Boltzmann *entropy* (see Section 3.2) of R is higher than that of $\bar{R}$, which makes the transitions $\bar{R} \rightarrow R$ and $R \rightarrow R$ jointly more probable than $R \rightarrow \bar{R}$. If one defines the *complexity* associated with a macrostate as the number of distinct bigrams encountered in its microstates, as in **(c)**, then R has a higher complexity than $\bar{R}$, namely, 3, compared to 1.

My focus here is on Boltzmann entropy, in terms of which the Second Law of thermodynamics is formulated (Lesne, 2014). For this entropy to be well-defined, one must classify the system's states into categories, or *macrostates*, such that all the (micro)states

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[6] The title of (Brandon and McShea, 2020) — "The Missing Two-Thirds of Evolutionary Theory" — refers to adaptation, diversity, and complexity, of which they claim only the first has been properly accounted for in the literature.

[7] This clarification fits precisely the spirit of Darwin's original remark on the evolution of complexity.

[8] A biologically relevant configuration space could be, for instance, the space of genomes (Jeffery et al., 2019, p.12).

belonging to a given macrostate are equivalent according to some criterion (which must be non-arbitrary; Brooks and Agosta, 2012, pp.502-503). The entropy of a macrostate is then proportional to the logarithm of the number of microstates that belong to it (that is, have the same macroscopic properties). Assuming the probabilities of transition between any two microstates are all the same,[9] it then follows that the succession of the system's macrostates over time is likely to proceed in the direction of increasing entropy. The reason for this is straightforward: an entropic transition—from a macrostate that contains fewer microstates to one that contains more—is more probable (see Figure 1 for an illustration of this argument).

A few clarifications gleaned from the literature should help us understand how complexity, entropy, and the Second Law are related to each other:

- Entropy is not the same as complexity. [McShea (1997), p.88] points out that "Entropy is a relationship between microstates and macro states, while complexity is a property of a single microstate, of one specific composition and configuration, and involves no such relationship (Wicken, 1987). Complexity is not entropy." For a discussion and an explicit computational model of the two, see (Aaronson et al., 2014).
- Entropy is not simply disorder. [Lesne, (2014), p.56] explains: "Rather than a measure of disorder, entropy is a measure of the typicality of the disorder, that is, a measure of degeneracy: how many configurations share the same macroscopic observables and constraints."
- The foundation of the Second Law is probabilistic (as noted above, it is only this foundation that I invoke here). This key fact is, unfortunately, not recognized by McShea and Brandon, (2010), who write (p.12): "We advise readers against [making a leap from the ZFEL to the second law of thermodynamics], for their own safety. We are concerned that on the other side of that leap there may be no firm footing. Indeed, there may be an abyss . . . [W]e think the foundation of the ZFEL lies in probability theory, not in the second law or any other law of physics." In fact, though, while the ZFEL is indeed not the same as the Second Law, they both are probabilistic.
- The Second Law does not contradict the growth of entropy within biological *systems*. Brandon and McShea (2020), p.25 write: "If left to its own, the second law predicts a cold gray uniform wasteland." Living systems stave off the action of the Second Law by acquiring and spending energy to maintain their structure, in a process that is commonly seen as the opposite of entropic. However, as Brooks and Agosta (2012), p.504 note, "It is more complete to recognize that biological systems maintain low-entropy states relative to their surroundings, *but not relative to their own previous states.*"

This latter observation is key in understanding how complexity growth in a biological system can be entropic. The following intuition has been offered by [Wicken (1979), p.362]:

> We know the Second Law to be a disordering principle which establishes the directions of all natural processes. How can the ontogenic or evolutionary development of these "ordered" biological structures be explained by the action of a disordering directive in nature? This apparent paradox evaporates once the word "order" is confined to its proper denotative realm. Biological structures are not "ordered" in the sense prescribed by information theory; they are "organized." The Second Law acts to dissipate order, not organization; indeed the latter tends to accumulate at the expense of the former.

Wicken's formal analysis of organization, which he applied to the complexity of evolving molecular structures, is too technical to recount here, but its bottom line is clear:

> [T]he [complexity-increasing] tendency in evolution can be derived from the overall randomizing operation of the Second Law, that, given the particular set of physicochemical constraints under which it operates, the Second Law leads naturally to progressively higher levels of complexity. (Wicken, 1979, p.361)

Brooks (Wiley and Brooks, 1982; Brooks, 2001; 2011; Brooks and Agosta, 2012) has made the formal case for this explanation in a general evolutionary setting, using the same parts-based notion of complexity as McShea and Brandon (2010). [Brooks and Agosta (2012), p.505] further explain that one of the classes of processes that generate entropy is

> . . . expansion of the realm of possibilities (the phase space) in which the system resides, increasing its number of accessible microstates (possible configurations). System organization increases so long as equilibration (equiprobable distribution of the system over its microstates) occurs at a slower rate than the expansion of the phase space . . . So long as the phase space expands faster than the system can fill it up, increasing entropy can be accompanied by the emergence of organized structure[10].

A discussion, and a formal connection, between the intuitive concepts of "organized structure" and complexity can be found in

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[9] This corresponds to my assumption in this section that the system's traversal of its configuration space is due to drift and is not biased or forced.

[10] This passage continues as follows (Brooks and Agosta, 2012, p.505): "In cosmology, this argument explains the spontaneous and irreversible emergence of stars, solar systems, galaxies, and other organized structures, in which fundamental forces linking material bodies, like gravity, slow down the entropic diffusion of matter in the universe to such an extent that organized structures emerge as a result of increasing entropy." These ideas are related to the anthropic principle in cosmology (Giudice et al., 2019; Wallace, 2019) and to Smolin's (1997) Cosmic Natural Selection (CNS) framework, which posits that the fine-tuning of cosmological parameters is selected for (across universes) by the appearance of a conscious observer.

(Aaronson et al., 2014). For a recent restating of the idea that evolutionary complexity growth can be entropic, along with an accessible discussion of the probabilistic foundation of the Second Law, see (Jeffery et al., 2019).

To summarize the materials that I have reviewed so far, passive evolution (in the absence of selection) has a tendency to increase the complexity of the systems that are subject to it, through at least two distinct mechanisms: the combination of variation with heritability (per the ZFEL) and the entropic dynamics of complexity (per the Second Law of thermodynamics). In the next section, I consider how selection forces can facilitate (or thwart) the passive evolution of complexity.

4 The effects of selection

Like passive random-drift evolution that I have just surveyed, selection-driven evolution too can give rise to increasingly complex systems through several distinct mechanisms. One of these is entropic drift that happens when the number of microstates grows faster than they can be randomly visited. [Collier (1998), p.136] points out the analogy and explains how it results in a non-equilibrium (in the thermodynamic sense) and entropic evolutionary growth of complexity under environmental selection:

> One possibility involves entropic increase of information, along the lines described by Brooks and Wiley . . . in the absence of adaptation. If we assume that the environment contains genetic variation, much as a bell jar contains a gas, then we have a source of cohesion that allows us to distinguish genetic macrostates (the environmentally constrained state) from genetic microstates (all of the variant states permitted by a particular environment). . . . One reason to expect non-equilibrium is [that] as new variants are selected, the genome becomes more highly adapted, constraining the genetic phase space more severely. On the other hand, the same process often opens up new possibilities for adaptation, which constitutes a release of constraints, possibly making more genetic information potentially adaptive. This would increase the effective genetic phase space.

Note how this argument echoes Darwin's remark (quoted in the epigraph), to the effect that all species stand to gain complexity "from the new relations caused by the advancing complexity of others."

Another selection-based mechanism that can contribute to the growth of genomic complexity of organisms over consecutive cycles of replication with mutations has been described by Adami et al. (2000). These authors define the complexity of a (fixed-length) genome as its length minus the sum of entropies for each of its sites. In a simulated evolution experiment, complexity thus defined has been shown to grow monotonically, except for occasional drops associated with those mutations that precipitate major evolutionary transitions. Given that such mutations amount to the environment performing a fitness measurement, the increase in complexity can be understood in terms that are familiar from thermodynamics: ". . . because natural selection forces genomes to behave as a natural "Maxwell Demon," within a fixed environment, genomic complexity is forced to increase" (Adami et al., 2000, p.4463). A recent book-length synthesis by Adami likewise focuses on the effects of selection on "functional complexity" (Adami, 2024, ch.5)[11].

5 Emergent signatures of evolution: directionality and historicity

I now proceed to outline a common conceptual framework for the different types of complexity-increasing mechanisms discussed so far. By definition, a common characteristic of all evolutionary processes, whether passive or driven, that contribute to the growth of complexity is *directionality*. Passive processes, which depend on random changes in complexity over time, must incorporate a mechanism that makes a decrease in complexity less likely than an increase, or else the average complexity will remain stable. Thus, for systems that are subject to the ZFEL, the directionality is a (perhaps counterintuitive) consequence of the mathematics of heritable random variation. For unbiased entropic systems, characterized by distinct levels of micro- and macro-states and a fast proliferation of the former, it is a consequence of the probabilistic basis of the Second Law of thermodynamics. An analogous argument (see the above quote from Collier, 1998) applies also to the evolution of entropic systems that are selection-driven. Lastly, the Maxwell Demon analogue that arises out of the combination of mutations and selection is inherently directional.

The directionality of the evolutionary change of complexity has been described as a *ratchet* effect (e.g., Tennie et al., 2009; Brooks and Agosta, 2012; McElreath et al., 2018; De Castro and McShea, 2022; Scerri and Will, 2023).[12] This name is somewhat misleading: as we have seen, directionality does not require a dedicated, explicitly one-way mechanism (a ratchet). Rather, it can *emerge* from the dynamics of the evolving system—as is the case in all the examples discussed so far in this paper and summarized in the opening paragraph of this section.[13] A general characterization of ratchet-

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[11] Adami's notion of genomic complexity is functional in that it defines complexity in terms of the amount of information that a genome stores about its environment. With this definition in place, simulated evolutionary dynamics of populations of digital organisms show that selection acts as an effective filter that "prefers" higher-over lower-complexity organisms (thus the analogy with Maxwell's Demon, a celebrated thought experiment in thermodynamics; see Maroney, 2009). Wong et al. (2023) have likewise offered arguments for the evolutionary increase of what they term "functional information." For a review of Adami's book, see (Kampourakis, 2025).

[12] By analogy with the class of mechanical devices in which a spring-loaded tooth allows a rotary or linear gear to move in one direction, while preventing the reverse motion.

[13] Additional examples of ratchet-like processes include Collier's (1998) "generative entrenchment" and "constructive neutral evolution" of [McShea et al. (2019), p.1111]. McElreath et al. (2018) distinguish between primary and secondary ratchet mechanisms. Scerri and Will, (2023) argue that a "critical mass" is needed for the ratchet dynamics to pick up. Ratcheting of cultural transmission in humans, compared to chimpanzees, is discussed by Tennie et al. (2009).

like dynamics offered by Brooks and Agosta (2012), p.504) is helpful here: “There is no distinction between ratchet irreversibility and temporal irreversibility—ratchet irreversibility is the establishment of temporal correlations strong enough to limit the options the system can explore.”

The other emergent signature of evolution, arising out of its directionality and irreversibility, is path dependence or *historicity*. This is the feature that prompted some authors to refer to the creatures of evolution as “victims of history” (Wiley and Brooks, 1982)[14] or, less ominously, “children of time” (Brooks and Agosta, 2012). Historicity consists in the observation that any particular configuration, such as the distribution of traits in a population or species in an ecosystem, is necessarily constrained by the sequence of steps whereby it emerged from an earlier state. These serve to jointly “explain” the present state, the scare quotes being due to the general impossibility of projecting the explanation into the future: postdiction may be possible, but prediction, in typical complex evolutionary systems, is not (Annila and Salthe, 2010; Longo, 2018; Ereshefsky and Turner, 2020; Tahar, 2022)[15].

The not-quite-explanatory nature of historical accounts underlies the problematicity of some of evolution theory’s key tenets, whose popular phrasing makes them appear circular. Thus, evolution by natural selection is tautological when reduced to the familiar slogan “the survival of the fittest,” as the best answer to the question it begs — “Which are the fittest?” — would seem to be “Those that survive.” Of course, as Ernst [Mayr (1976b), p.13] has explained, Darwin’s actual formulation involved no tautology.

Morgan (1910), p.210 invokes a similarly structured popular sentiment (italics mine): “The mechanism of survival (if I may be pardoned the expression) is such that it insures success where it is most called for. To repeat a familiar epigram: *In evolution nothing succeeds like success*.”[16] [Mayr (1976a), p.34] unpacks this latter expression:

> We have a proverb that is applicable here, “Nothing succeeds like success,” and this is the secret of natural selection. Success, in this case, means leaving offspring. But what is it that determines this success? If success were determined by blind chance, as are most processes that lead to genetic variation, we would not be justified in speaking of natural selection, for selection implies discrimination. But, and this is the cornerstone of the evolutionary theory since Darwin, it is justifiable to refer to differential reproduction as natural selection because individuals differ from each other in their genetic endowment, and it is, at least in part, the nature of this genetic endowment that determines reproductive success.

Thus, it is the dependence of evolutionary success on the inherited genetic endowment that underscores the historicity of evolution and at the same time ensures that the central thesis of evolutionary theory is not circular.

The various mechanisms I have reviewed so far, which explain how complexity of living systems can increase over time, suggest that on top of the characteristic of evolution as a process in which “nothing succeeds like success” one might add another one: “complexity breeds complexity” (McDonald Pavelka, 2002; Andersson et al., 2014). This slogan, which fits well the quote from Darwin’s notebooks that opened this paper, can also serve as a bridge to the next section, in which I take up the question of complexity as applied to consciousness.

6 Complexity and the evolution and learning of consciousness

The mass revival of scientific interest in consciousness in the 1990s included proposals for quantifying the complexity of brain activity, under the assumption that the neural substrate of consciousness is necessarily complex. A prominent proposal, due to Tononi and Edelman (1998), introduced a measure of “neural complexity” that combined integration and differentiation of brain activity—the former because of the phenomenal unity of conscious experience, and the latter because of its richness depending on discernment among various possible experiences (in other words, consciousness is differentiated because it involves and discerns many varied experiences).

Two decades later, a comprehensive review by Sarasso et al. (2021) revealed a general acceptance in consciousness studies of the tenet stating that “the presence of consciousness is invariably associated with high brain [activity] complexity” (p.3). The validity of this sweeping generalization can, however, be questioned, in view of the wide variety of cognitive processes that are subsumed under the rubric of consciousness. These range from the basic phenomenal awareness of certain aspects of the world as represented in a cognitive system, to self-awareness and the awareness of awareness. It is the latter varieties that are most often referred to as consciousness in informal discussions[17].

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[14] “History as evolution” is the title of (Nunn, 2021).

[15] The course of evolution is impossible to predict, as noted among others by Annila and Salthe (2010), p.307: “The simple equation of evolution (Equation 5)… is surprisingly insightful. To begin with, it cannot be solved.” Likewise, Doulcier et al. (2021) write that “… a general value of fitness that is both explanatory and predictive cannot be attained.”

[16] Compare this to [Quine’s (1969), p.124] remark about the course of science: “In induction, nothing succeeds like success.” See also (Edelman, 2023, p.39).

[17] For an illustration, see (Edelman, 2023, Figure 1.1). An extensive list of the different meanings of the term “consciousness” can be found in (Natsoulas, 1981). More recently, [Metzinger (2003), p.3] has remarked that “it is simply not true that everyone has a rough idea of what the term ‘consciousness’ refers to. In my own experience, for example, the most frequent misunderstanding lies in confusing phenomenal experience as such with what philosophers call ‘reflexive self-consciousness,’ the actualized capacity to cognitively refer to yourself, using some sort of concept-like or quasi-linguistic kind of mental structure. According to this definition hardly anything on this planet, including most humans during most of their day, is ever conscious at all.”

In contrast, here I focus on *phenomenal awareness*, encompassing basic qualities of ongoing experience, such as salty or red. Very importantly, basic phenomenal awareness can become relatively more complex (over evolutionary time or due to learning), as when more shades of red become discernible, without the system supporting it being necessarily complex in absolute terms, in the sense of Sarasso et al. (2021).

6.1 Basic phenomenal awareness as autodiagnosis

Basic phenomenal awareness always involves discernment, as in telling apart salty from sweet, bitter, etc.,; or red from green, yellow, and so on. According to my working hypothesis, the Dynamical Emergence Theory or DET (Moyal et al., 2020), this simplest variety of consciousness consists in dynamically emergent diagnosis by the system in question of its own representational states—what may be called *autodiagnosis*. I stress that basic consciousness, on this account, does not "arise" out of this dynamics: rather, it *is* (the process of) autodiagnosis[18].

Importantly, this level of phenomenal awareness does not require a brain as complex as that of humans and is arguably present in insects (Edelman et al., 2016) and even single-cell life forms (Edelman, 2023, ch.1-2).[19] At the same time, the emergence of autodiagnosis does seem to reflect an increase of some measure of the diagnostic system's complexity. Such an increase may happen (i) over evolutionary time, and/or (ii) over the lifetime of the system in question, as it learns to discriminate among its own states.

The capacity for diagnosis has already been explicitly linked to the thesis of the evolutionary increase of complexity by Collier, (1998), Collier, (2000). [Brooks and Agosta (2012), p.503] explain the connection as follows:

> Collier (1998), Collier (2000) related information to the causal capacity of a system, its ability to impose distinctions on its surroundings. Collier proposed that physical (material) information systems occur as arrays, or multi-dimensional messages, in which the information has . . . a real (*non-arbitrary*) macrostate/microstate distinction [my emphasis].

Interestingly, a non-arbitrary macrostate/microstate distinction is central also to the DET account of phenomenal awareness, which identifies the "stream" of awareness with the succession of emergent metastable macrostates (*cf.* Crutchfield, 1994) in the system's state space (Moyal et al., 2020). It is important to note that for this explanation of phenomenal awareness to hold, the delineation of macrostates cannot be arbitrary (hence my emphasis in the above reference to Collier's work). Nor can it be up to an external observer: the only diagnosis that is relevant to consciousness is autodiagnosis (by the system of its own states). In DET the macrostates are non-arbitrary because they are, by definition, equivalence classes of future predictability (in other words, a macrostate bundles together microstates whose successors are also likely to be bundled together). Macrostates are thus *causal* (rather than merely epiphenomenal) in that they render the system's future trajectory through sequences of macrostates conditionally independent of its past (Crutchfield, 1994, p.26).

6.2 How basic phenomenal awareness can become more complex

Any opportunity for refining such trajectories through the modification of the system's dynamics may open an entropic (in the sense spelled out earlier in this paper) path towards increasing complexity of phenomenal awareness. Such an increase can happen as the system's architecture changes over evolutionary time, or during the lifetime of an individual, as the system learns.

The former type of change is exemplified by the increasing capacity for discernment, and the concomitant growth in complexity, in the evolution of visual systems (see, e.g., Feinberg and Mallatt, 2013).[20] The scale of evolutionary complexity here can be illustrated by a side-by-side comparison of (1) simple photosensitivity, which allows for the distinction between light and dark and the detection of a passing shadow, as in the ocelli eyespots of planarian flatworms (2) the emergence of an imaging "camera" eye, allowing the discrimination of moving spots and edges and much more, as in frog vision; (3) complex shape perception afforded by cortical processing, as in mammalian visual systems; and (4) color perception, which adds extra nuance and discernment. (The present coexistence of all these types of visual systems shows that evolutionary complexification is a tendency, rather than an "across the board" process, as already noted in this paper).

Consider now complexification due to learning, illustrated by the following progression in the development of expertise in wine tasting: wine/red wine/red Rioja/red Coto de Imaz/red Coto de Imaz 2016. As tasters learn to tell apart samples that hitherto appeared to them indistinguishable, intuition suggests that the complexity of their phenomenal experience of the taste of each sample should grow—say, from the simple two-way distinction between red wine and white wine to the experience of the sample as a wine of specific variety, vineyard, and vintage, as distinguished from hundreds of others that the taster is now capable of identifying.

On an abstract computational level, both evolutionary and learning-induced complexification are accounted for by DET in the same manner. Consider the cognitive system's *trajectory space*, in which each entire trajectory through its state space corresponds to one point. DET equates the complexity of a system's experience with the topological complexity of this trajectory space (Fekete and

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[18] To be clear, the consciousness-related parts of the present paper are not intended to defend the DET (let alone to compare it with other theories of consciousness). Rather, I argue that, from within the DET framework, complexity of the system's dynamics identified with consciousness tends to increase.

[19] For discussions of cognition in single-cell organisms, see (e.g., Tagkopoulos et al., 2008; Lyon, 2015; Godfrey-Smith, 2016; Lyon and Kuchling, 2021).

[20] I thank a reviewer for suggesting this example of complexification of (visual) awareness over evolutionary time.

Edelman, 2011; Moyal et al., 2020).[21] The higher the topological complexity of this space,[22] the more intrinsically distinct points—that is, trajectories—it contains and, correspondingly, the richer its repertoire of phenomenal experiences (which is what the trajectories *are*)[23].

A similar conclusion regarding the complexification of a phenomenally aware system's dynamics through learning can be reached by considering its entropy as defined classically, in terms of micro- and macrostates. Learning of better discernment from experience involves an increase in the number of microstates, as newly encountered items come to be represented in the system's memory, and in the number of macrostates, as the creation of new categories becomes possible (per the wine hierarchy example). This makes the process whereby an individual system acquires expertise entropic, in that the system's total entropy (as measured by a sum over its macrostates of the logarithm of corresponding numbers of microstates) increases with learning. We may thus conclude that as the acquisition of exemplars and categories proceeds, the system is unlikely to revert through mere random drift in the configuration space to a lower-expertise configuration—which, according to DET, corresponds to less-discerning awareness.

I note that reinforcement learning could modulate this process, either amplifying or countering it. Likewise, on the evolutionary level, selection may effectively amplify it (if expertise proves to be adaptive), or not—as discussed above in the context of the interaction of neutral and selection effects. Note that both the individual- and the evolutionary-level processes that make phenomenal awareness more complex work not just for wine expertise, but also for any other experiential quality that is amenable to refinement through learning (as well as for sets of such qualities that are mutually commensurable, that is, belong in the same psychological space in the sense of Shepard, 1987). Thus, the hypothesis stated in the opening paragraph of the present paper—that the evolutionary tendency towards increasing complexity might extend to what I call basic consciousness—seems to be compatible with my analysis both of the notion of complexity itself and of its application to the evolution and learning of conscious discernment (by the system of its phenomenal states).

6.3 A possible test case: entropy and complexity in a reservoir computing model of insect olfactory discrimination

As a setting for exploring the relationship between basic phenomenal awareness and complexity, I propose to consider reservoir computing (RC), also known as an echo state or liquid state machine (Natschläger et al., 2002; Maass and Markram, 2004; Maass, 2007; Cucchi et al., 2022). An RC machine consists of (1) a "reservoir" of coupled neurons (biological or not) characterized by nonlinear dynamics, which may be perturbed by an external input, and (2) a linear readout circuit, which sets the system's output to a weighted sum of the neurons' activities. The connections among reservoir neurons may be fixed, or they may be subject to learning so as to optimize its dynamics. The readout weights are always trainable and can be adjusted to produce desired outputs in response to certain inputs. The computational power of the RC architecture is well-understood (see the many references in Seoane, 2019). Here, I focus on its capacity for intrinsic discernment, which DET equates with basic phenomenal awareness.

An RC machine responds to inputs by tracing out trajectories within the volume of the state space spanned by its units' activities.[24] If the system is subject to metabolic constraints, the reservoir neurons will tend by default to be largely quiescent, such that the (micro)states accessed by these trajectories cluster near the origin, comprising just one macrostate. Through reinforcement learning (Pack Kaelbling et al., 1996) or evolution (Watson and Szathmáry, 2016; Frank, 2023), the trajectories begin to venture away from the origin (drawing on an energy resource). As finer and finer discernment is attained, the number of intrinsically distinct macrostates grows, resulting in higher entropy (as noted earlier)[25].

The RC architecture naturally maps onto that of the key circuit in the olfactory system in insects such as the locust (Mazor and Laurent, 2005; Broome et al., 2006) or fruit fly (Kennedy, 2019; Gkanias et al., 2022). Specifically, the nonlinear dynamics is implemented by a reservoir of recurrently interconnected projection neurons in the antenna lobe. These project to Kenyon cells in the mushroom body, which carry out linear readout (Buzsáki, 2010). The several experiments proposed in the appendix would capitalize on the RC interpretation of this neural circuit, making it possible to test the thesis of the present paper on a real-life example.

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[21] An alternative definition of the complexity of phenomenal experience is part of the Integrated Information theory of consciousness (Oizumi et al., 2014); for a critique of the latter, see (Fekete et al., 2016).

[22] Intuitively, the number of connected components, holes, etc.,; see (Carlsson, 2009) for a formal introduction. Examples of the application of computational topology in quantifying the complexity of brain activity can be found in (Singh et al., 2008; Fekete et al., 2009). Topological complexity is not to be confused with *topological entropy*, which "describes how many trajectories are required to span the phase space with a prescribed resolution" (Lesne, 2014, p.39).

[23] Two trajectories are qualitatively distinct just in case the two points representing them in the trajectory space belong to topologically distinct (disconnected) subsets of the set of all trajectories that can be realized by the system. The emergence of a new discernment in the trajectory space proceeds as follows. In a system that does not implement discernment, the set of all trajectories is a simply connected region of the trajectory space. The emergence of a two-way discernment corresponds to this set being split into two mutually exclusive ones, such that no continuous deformation maps a trajectory in the first subset into a trajectory in the second one. Trajectories in the two subsets are now (intrinsically) qualitatively different.

[24] Notably, in evolutionary biology the phase space is not "given" (Longo, 2020; Tahar, 2022).

[25] Evolutionary paths to (and from) RC are discussed and illustrated in (Seoane, 2019, Figure 4).

7 Concluding remarks

In the opening paragraph of his paper *The law of evolution as a maximal principle*, [Lotka, (1945), p.167] dismisses complexity increase as a poor candidate for a general law, arguing that "If . . . it is stated that evolution proceeds from simpler to more complex forms, . . . the direction of evolution is but poorly defined, for the rule is one with disturbing exceptions, and what we seek is not an empirical rule, but a law of nature that brooks no exceptions." My conclusion from the present review is that if one follows [Darwin (1960), note 95] in seeking a general *tendency* rather than a universal law, then complexity increase does emerge as a non-trivial principle of evolution, underwritten by several distinct mechanisms. Moreover, this principle seems to apply not just to the evolution of species' morphologies — "endless forms, most beautiful" — but also to the evolution and learning of their capacity for phenomenal discernment, which constitutes the most basic level of consciousness[26].

Given how controversial the hypothesis of evolutionary increase in complexity has been over the decades (and still is), it is not surprising that its empirical assessment is not often attempted. Some experiments in simulated evolution did yield support for this hypothesis (e.g., Adami et al., 2000; Yaeger, 2014; Beslon et al., 2021). Particularly interesting are the study of the evolution of complexity in *Drosophila* under weak selection (Fleming and McShea, 2013) and a much broader-scope investigation of the evolution of complex multicellularity, for which the authors offered a nonadaptive explanation (Bingham and Ratcliff, 2024).

Assuming that complexity increase is a common enough evolutionary tendency, one may ask whether its rate remains steady or grows with time (as suggested by Darwin in the note quoted in the epigraph). The growth of complexity is indeed expected to accelerate in cases in which greater complexity facilitates evolvability (Watson and Szathmáry, 2016; Fields and Levin, 2020). It can also accelerate if biology co-evolves with *culture*—a well-known catalyst of change that is cumulative (e.g., Tennie et al., 2009; Szathmáry, 2015; McElreath et al., 2018) and therefore self-reinforcing. To repeat a phrase that came up earlier in the present paper, "complexity breeds complexity" — as anthropologists have been arguing for a while (Andersson et al., 2014, p.162) (a computational modeling study (Kolodny et al., 2015) suggests, however, that cultural complexity may increase exponentially, or polynomially, or asymptotically, depending on conditions)[27].

Further exploration of this and related topics should proceed in full recognition of the applicability of the idea of evolutionary growth of both entropy and complexity across what Aberle, (1987) called "historical sciences": his own disciplines of anthropology and sociology—where full-blown human consciousness and not just basic phenomenal awareness is of critical importance (Edelman, 2023, ch.7) — as well as evolutionary biology, geology, and cosmology. Citing Layzer, (1972) and Brooks and Wiley (1985), Aberle endorses an approach that "makes culture a part of nature—of the biosphere and the cosmos" (Aberle, 1987, p.561). Broad as it is, the scope of such an approach to the evolutionary dynamics of complexity can be extended even further by taking up the cosmological selection hypothesis (e.g., Smolin, 1997; Giudice et al., 2019), according to which evolution applies also across universes. That extension will, however, have to await future research.

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Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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[26] Lotka's proposed law stated that "Evolution, in these circumstances [available mass and energy] proceeds in such direction as to make the total energy flux through the system a maximum *compatible with the constraints*" (1945, p.187). On the same page, Lotka remarks that "One is inclined here to give at least qualified assent to the saying of Herodotus: 'If one is sufficiently lavish with time, everything possible happens.' " (1945, p.187, footnote 30). Of course, one thing that evolution does not lack is time. When combined with the various ratchet mechanisms (recall section 5), this realization may help us understand why complexity does, after all, tend to increase over the eons.

[27] The notion that complexity breeds complexity appears also in sociology, economics, and management works (e.g., Venkataraman and Van de Ven, 1988), as well as jurisprudence, where its connotations are typically negative (e.g., Haddon-Cave, 2021).

Publisher's note

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Appendix: proposed experiments

The four experiments outlined below involve a reservoir network model of the projection neuron / Kenyon cell circuit in insect olfaction.

Experiment 0

Initialize a reservoir network (no linear readout is needed in this experiment) with close-to-zero weights. Perform a random walk in the weight space, corresponding to neutral evolution. Define microstates by quantizing the trajectories, and macrostates by clustering the microstates. With the Zero-Force Evolution Law in mind, I predict that both the entropy of the reservoir and the topological complexity of its dynamics (as measured by persistent homology; see above) will increase.

Experiment 1

Repeat experiment 0, but initialize the RC with random weights, uniformly distributed in the interval between zero and a maximum weight. The tendency of the entropy and complexity of the RC's activity to grow should now be less pronounced than in experiment 0.

Experiment 2

Use a genetic algorithm (Booker et al., 1989) to conduct an evolutionary search in the parameter space of a reservoir network, combined with reinforcement learning of the weights of the linear readout, the objective being discernment among multiple "odorants," carrying positive, neutral, or negative rewards. As before, define microstates by quantizing the trajectories, and macrostates by clustering the microstates. I predict that over evolutionary time both the entropy of the system and the complexity of its dynamics will tend to increase, subject to interaction with other variables in the system.

Experiment 3

As in Experiment 2, but drive the RC weights and the linear read-out weights by performance in a prediction task (cf. Morales et al., 2021). This experiment is motivated by the apparent link between prediction and entropy (Still et al., 2012), as well as its central role across all of cognition (Friston, 2010) and, arguably, life itself (Friston, 2013).